MEASUREMENTS OF RADIATION EXPOSURE ON COMMERCIAL AIRCRAFT WITH THE LIULIN-3M INSTRUMENT

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Abstract

This paper reports on the development of a compact radiation monitor/dosimeter, the LIULIN-3M, and on extended measurements conducted on the ground and on commercial aircraft on domestic and international flights.

Introduction

The LUILIN-3M radiometer evolved from an international cooperative project by a group of Bulgarian, Russian, German, and American Scientists. The radiometer is a low power, small size, light weight, and low cost instrument composed of a solid state detector (SSD) with supporting electronics that enable it to operate as a pulse height analyzer of energy deposited in the detector, and to obtain from these measurements the total dose or the dose rate produced by charged particles. A flash memory allows self-storage of data during flights and post flight retrieval [1,2,3,4].

Description

The basic detector is a Silicon-Lithium Drifted diode, 1 mm thick, with a sensitive area of 1 cm^2, and a weight of 0.232 g. Figure 1 contains a block diagram that shows the supporting electronics. Charge pulses generated from the energy deposited by incident particles are passed to the charge sensitive amplifier, then to the discriminator and peak hold detector, and finally, they are converted from analog to digital signals by the 8-bit ADC (Analog-to-Digital Converter) and sorted into 256 channels, according to their voltage amplitudes. Two microprocessor units manage the data flow to and out of the memory devices.

The specifications and dynamic ranges of the instrument are listed in Table 1. The energy deposited or loss in silicon by the incident particles ranges from 0.16 to 13.8 MeV. The measurement time per spectrum of the instrument can be varied from 30 s to 30 min.

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Table 1. Specifications and dynamic ranges.

Specifications	Ranges
Mass: (including batteries) 960 g	Flux: 1 – 5000 part/cm^2-s
Size: 140 x 80 x 30 mm^3	Energy Deposited: 0.16 – 13.8 MeV
Temperature: -20°C to +45°C	LET: 0.16-13.8 kev/μ
Measurement Time: 30s to 30 min	

The LIULIN-3M operates in two modes, namely, "Working Mode" and "Data Transfer Mode". In the Working Mode, the switch "ON" button connects the instrument via a jack to a polarized relay. In this mode the device is operating under the control of the program in the microprocessors to collect dose, flux, and spectra until the memory is filled. At that time, the instrument is automatically turned "OFF" through the relay. The total time spent in the Working Mode is 480 hours. The expected lifetime of the lithium batteries is about 1000 hours.

In the Transfer Mode the device is switched "ON" after it is delivered to the principal investigator. This mode allows the transfer of the accumulated data in the flash memory to a personal computer (PC) under a parallel port communication link. During this mode the data are correlated to the real time of the flight.

The major parameter of the instrument is the amplitude of the charge pulses generated in the solid state detector by the incident particles. They are then passed to the charge-sensitive amplifier that converts them to corresponding voltage pulses. The sensitivity or conversion factor of this pre-amplifier is 240 mV/MeV. These signals are subsequently amplified by a factor of 5 in the main amplifier stage. The threshold setting of the discriminator is 38.7 mV which establishes the lower data limit and consequently, the number of channels assigned to noise signals. Since there are 256 channels in the Analog-to-Digital converter and the upper voltage limit is 3.3 V, the sensitivity per channel is 3.3/256 = 12.89 mV/Ch and thus the first three channels are assigned to storing noise pulses. The deposited energy (Dep E) is given by equation (1):

$$\text{Dep E(MeV)} = \Sigma_i \ (\text{counts}_i * \text{channel}_i) * M \qquad i = 4 - 256 \qquad (1)$$

where the conversion factor M is given by:

$$M = \left(12.89 \frac{mV}{Ch}\right) \Big/ \left(240 \frac{mV}{MeV}\right) = 0.05371 \ \frac{MeV}{Ch} \qquad (2)$$

and the corresponding dose rate per hour by:

$$\text{Dose Rate } D_R \ (\mu Gy_{si}/h) = K * \text{Dep E (MeV)} / t_c \quad (3)$$

where t_c is the collection time (in seconds) and the conversion factor K is:

$$K = 2.486 \text{ in units of } \mu Gy_{si} / h * MeV \quad (4)$$

Results

All data presented herein were collected on commercial flights every five minutes but the conditions of the measurements were not systematically controlled, particularly in terms of location and altitude. Figure 2 is a plot of dose rate versus minutes after the instrument was turned on for a flight from Washington, D.C. to Los Angeles, CA, Figure 3 covers the trip from Los Angeles to Auckland, New Zealand, and Figure 4 shows the last leg of the flight from Auckland to Christchurch, NZ.

Figures 5, 6, and 7 represent plots of measurements for flights from Washington, DC, to Denver, CO, Denver to Houston, TX, and finally, Houston to Denver then back to Washington the same day, respectively. Figure 8 is a summary plot of these four flights. Figures 9 and 10 show data taken on flights from Washington, DC, to Paris, France, and also on the return flight.

Figure 11 contains a plot of the instrument's measurements of dose rate versus time after turn-on for the Sofia-New York flight, indicating the background at the airport and the three data points for which the altitude levels are given. Figure 12 contains a plot of the data showing a curve fit to the four available data points versus altitude. Figure 13 depicts the data for the flights from Washington to Budapest. The measurements obtained on the return flight segments are plotted in Figure 14.

In most of the commercial flights, altitude information was made available by the Airlines after the flights; however, for the trip from Sofia, Bulgaria, to New York, NY, altitude data were provided to members of the LIULIN team on-board the plane by the pilot on three occasions, while on a recent flight from Washington, DC, to Frankfurt, Germany, to Budapest, Hungary, flight information (latitude, longitude, altitude, speed, temperature) was continuously presented on TV monitors in the cabin. It should be noted, however, that for some flights altitude data could not be obtained.

Discussion

For all flights reported in Figures 2 to 14, the peak dose rates are a function of two variables: altitude and magnetic latitude. Thus, in Figure 2 for the trip from Washington to Los Angeles the peak rate reached almost 0.2 μGy/5-min, whereas in Figure 3 for the trip from Los Angeles to Auckland, the dose rate remained around 0.07 μGy/5-min for

the major part of the flight over the Pacific Ocean, and only climbed to a peak of about .12 μGy/5-min near the end of the trip (last 2.5 hours). The dose rate for the short flight from Auckland to Christchurch, Figure 4, peaked at about 0.09 μGy/5-min.

In this context, particularly interesting are the measurements from the Los Angeles to Auckland flight, shown in Figure 3. The low dose rates would imply a correspondingly low altitude, perhaps 30000 feet, but the airline confirmed that this specific flight took place at an altitude of 39000 feet.

These measurements confirm that, as expected, flights toward lower magnetic latitudes, that is toward the magnetic equator, will experience smaller doses. The reason is that only a few very high energy galactic cosmic rays (several GeV/nucleon) can penetrate to those regions of the globe on account of the earth's magnetic field which deflects most arriving particles with lower energies (rigidity concept). The low dose rates shown in Figure 3 are probably due to the shielding effects of the earth's magnetic field which compensated for the normally higher cosmic ray progeny distribution at the elevated altitude of this flight.

The peak rates during the two flights covered in Figures 5 and 6,Washington-Denver-Houston, were about 0.15 and 0.13 μGy/5-min respectively. During the return trip, however, the peak rates achieved a surprisingly high level of 0.19 μGy/5-min for the Houston-Denver segment and 0.28 μGy/5-min for the Denver-Washington segment, as shown in Figure 7. The summary of these four flights is shown in Figure 8. The altitude of the aircraft, as given to us at a later date by the airline, was highest on the Houston-Denver (35000 ft) and Denver-Washington flights (37000) compared to the Washington-Denver (35000 ft) and Denver-Houston (33000ft) flight. It remains to be determined why the short duration Houston-Denver flight at 35000 ft experienced a higher dose rate (by ~ 20%) than the Washington-Denver flight at the same altitude but of much longer duration.

Figures 9 and 10 show data for a trip to Paris, France, and return to Washington, D.C. respectively. The longer flight time of about 6 hours shows that the rate was about constant for the flight to Paris, approximately 0.18 μGy/5-min, but on the return to Washington a constant rise in rate is observed, with a peak of about 0.23 μGy/5-min at the end of the trip as shown in Figure 10. Since we have no reliable altitude information for these flights, it is difficult to interpret the data correctly.

The flight from Sofia to New York provided for the first time an opportunity to measure the variation of the instrument's response in real-time as a function of altitude through the cooperation of the pilot. Figure 11 shows a plot of dose rate versus time after turn-on. During the trip to New York the plane flew at three different altitudes of 31000, 35000, and 37000 feet. It can be seen that the detector measured three distinct dose rates. Theses three rates are plotted in Figure 12 versus altitudes, including the background rate on the ground. A curve fit was made to the four data points and extrapolated to 40000 feet where the dose rate approaches 0.5 μGy/5-min.

In Figures 13 and 14 for the trip to Frankfurt-Budapest and return, again a similar pattern was observed as that seen in Figures 9 and 10 for the Washington-Paris and Paris-Washington flights, namely the trips east to Paris (Fig. 9) and to Frankfurt (Fig. 13) indicate a relatively constant level of exposure rate during the transatlantic voyage, whereas both return trips west show a gradual increase in the dose rate as the flights progress. Assuming that the flight corridor is the same for both directions, it is conjectured that the variation is altitude dependent, that is, lower altitudes going east and gradually higher altitudes going west, maybe in consideration of the jet stream (?). This will be investigated and resolved for the final paper.

All figures show low "background" measurements on the ground before take-off and after landing, ranging from 0.017 to 0.033 μGy/5-min. Upon close examination it is apparent that the data from low altitude locations like Washington, Houston, and Los Angeles, with elevations less that 100 feet, have almost the same values as data from elevated locations as, for example, Snowmass, CO, at over 9000 feet altitude (see fig. 8), that is: everage of about 0.0208 μGy/5-min and 0.0225 μGy/5-min, respectively. Since a noticeable difference in average dose rates should be observed at these two altitudes, the low elevation data may contain some level of instrument noise. The normal global average rate of radiation background levels, excluding high concentrations of naturally occurring radionuclides such as radium, thorium, uranium, etc., has been reported to be about 0.008 to 0.017 μGy/5-min at about 1 meter above ground and including cosmic ray contributions coming from above [5]. It has been established that the detector orientation has no discernible impact on the measurements, in flight or on the ground.

The total dose accumulation for each traveled flight segment will be calculated and presented in the full-length paper. As additional data are being accumulated over global distances with large longitudinal and latitudinal variations, a comparison to some predictions of cosmic ray intensities and their progeny may be possible, not only in terms of altitude but also as a function of rigidity and geomagnetic shielding affects.

Conclusions

The LIULIN-3M instrument is an effective radiation monitor for aviation or space application. It is characterized by small size, low power, light weight, and low cost. The instrument is currently being used to perform global surveys of radiation environment levels within aircraft and on high-altitude ballon missions over the south pole (U.S. Antarctic Program). Measurements from a multitude of commercial airline flights conducted so far, indicate a strong altitude and magnetic latitude dependence, as predicted by theory. The maximum dose rate encountered until now is about 0.3 μGy per 5-minute interval.

Acknowledgement

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DATE: (last updated) 7-29-99

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THE LIULIN-3M RADIOMETER BLOCK DIAGRAM

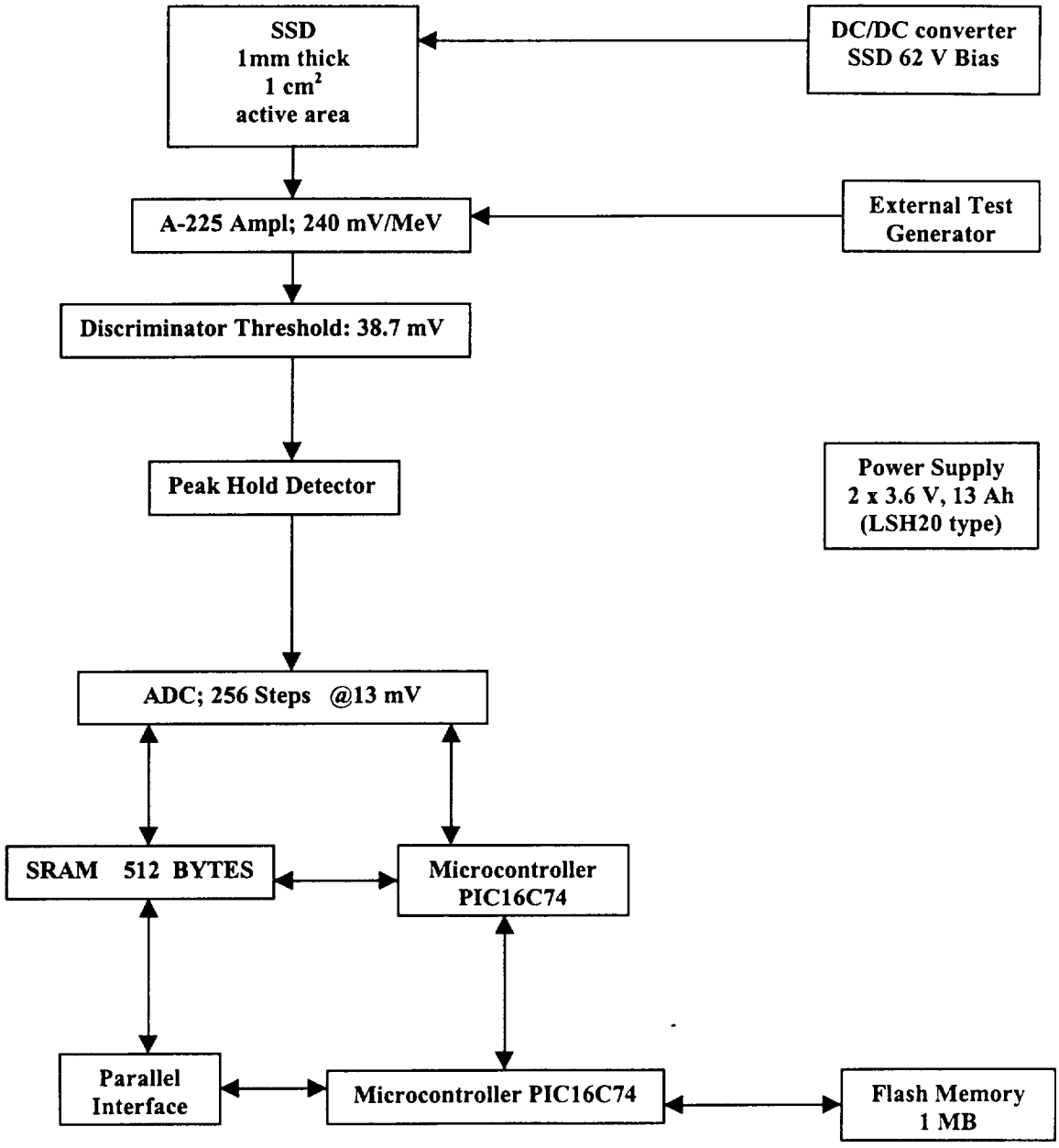

FIGURE 1

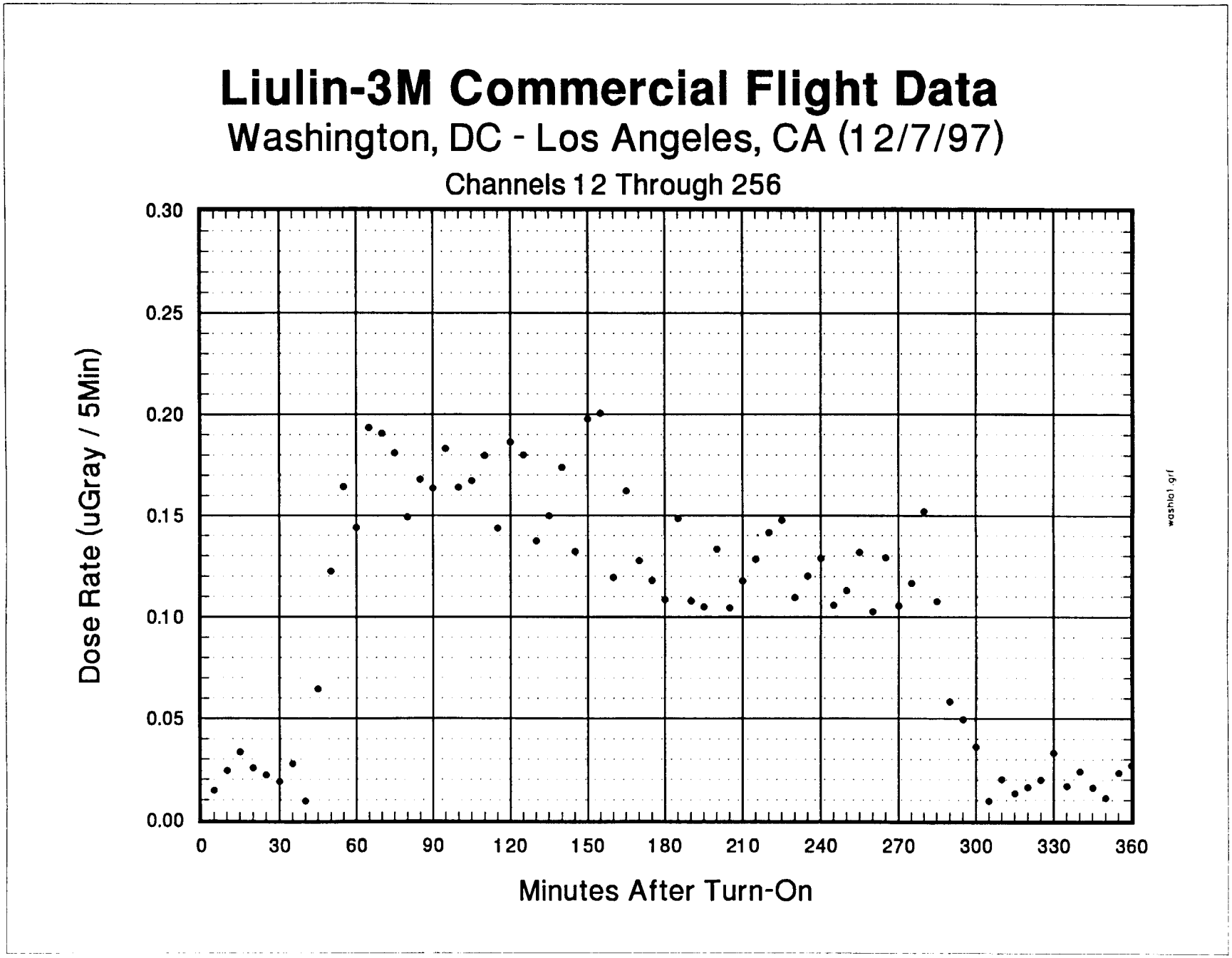
Liulin-3M Commercial Flight Data
Washington, DC - Los Angeles, CA (12/7/97)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
30
60
90
120
150
180
210
240
270
300
330
360
Minutes After Turn-On
washlo1.grf

FIGURE 2

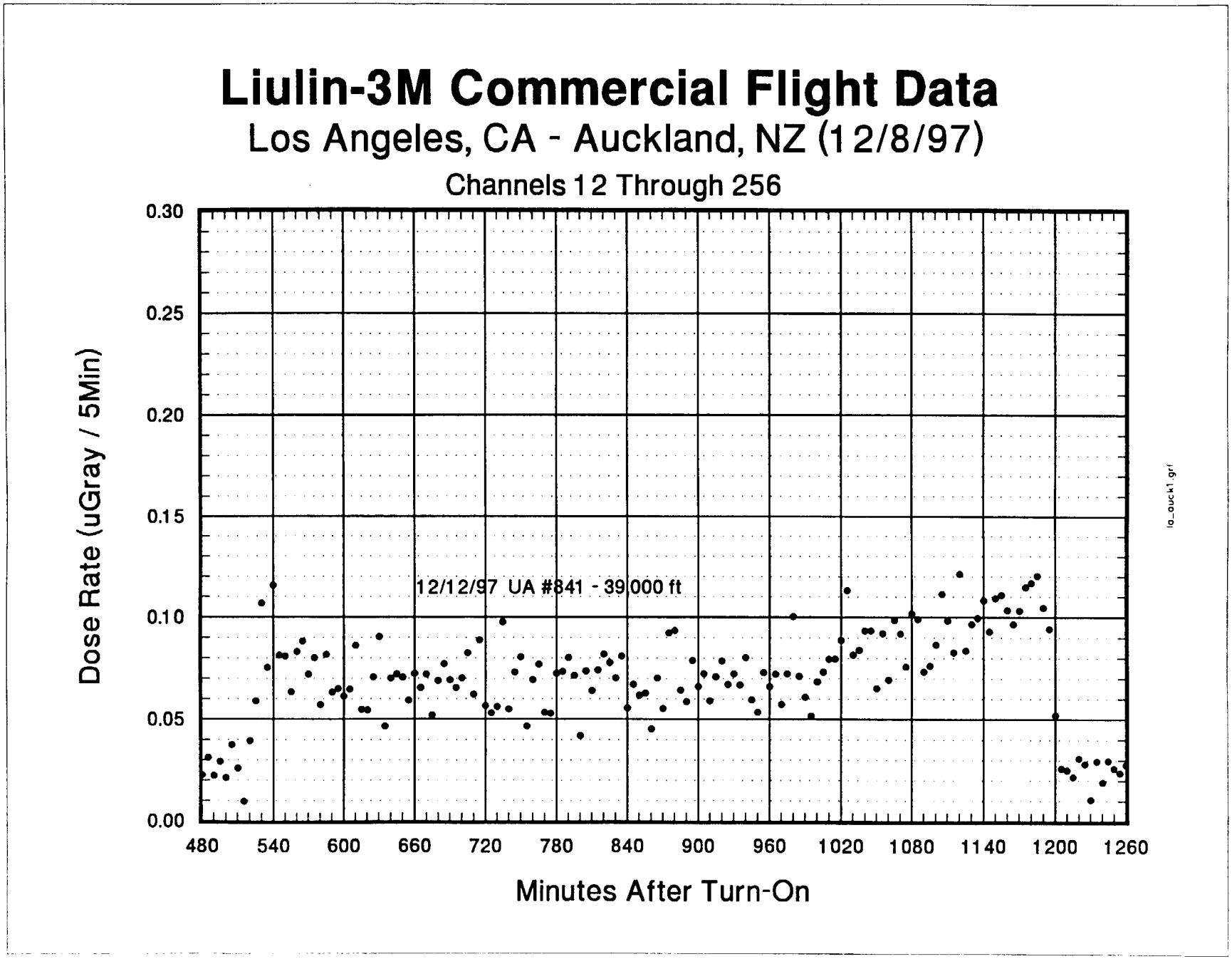
Liulin-3M Commercial Flight Data
Los Angeles, CA - Auckland, NZ (12/8/97)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
12/12/97 UA #841 - 39 000 ft
480
540
600
660
720
780
840
900
960
1020
1080
1140
1200
1260
Minutes After Turn-On
lg_auck1.grf

FIGURE 3

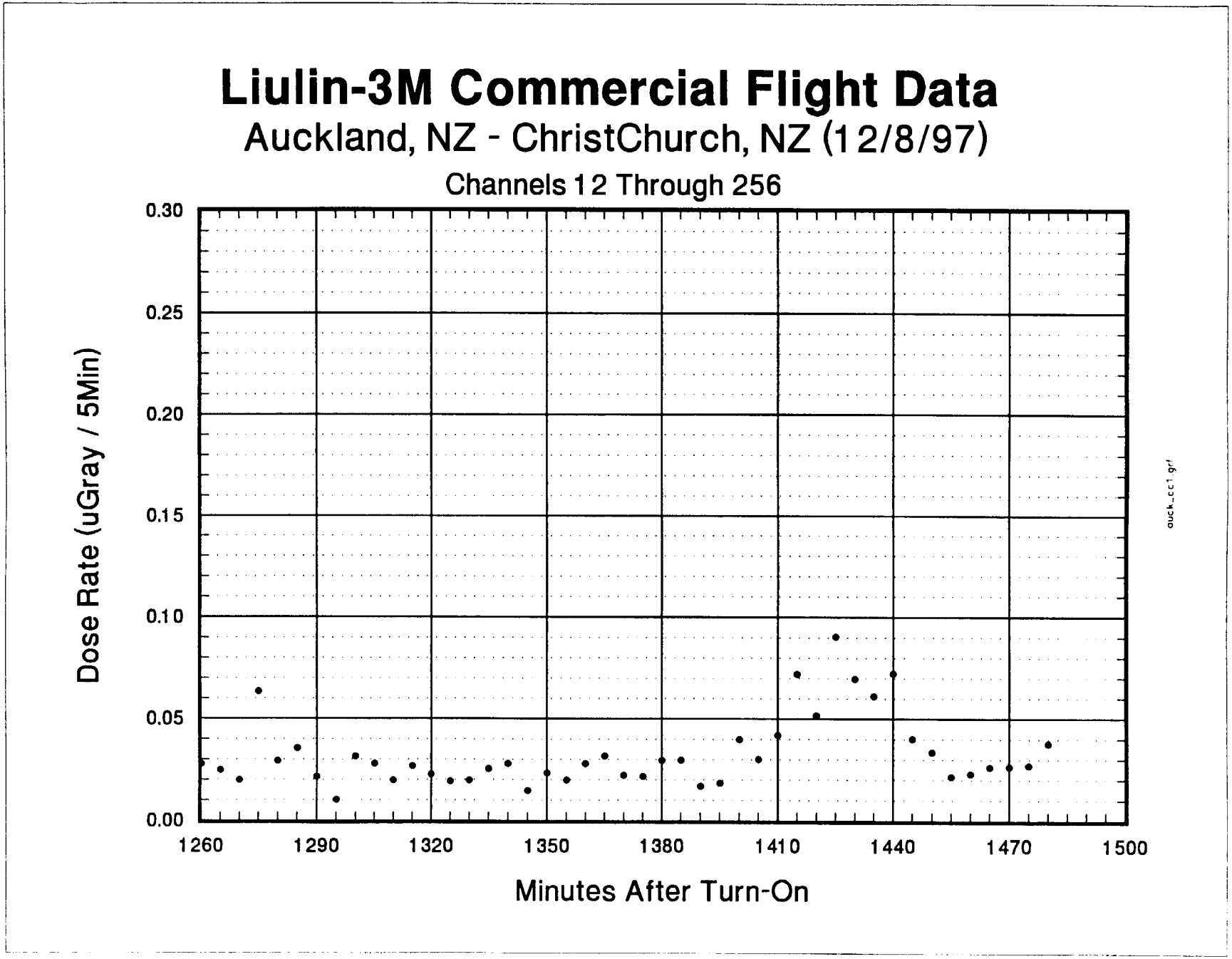
Liulin-3M Commercial Flight Data
Auckland, NZ - ChristChurch, NZ (12/8/97)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1260
1290
1320
1350
1380
1410
1440
1470
1500
Minutes After Turn-On
ouck_cc1.grf

FIGURE 4

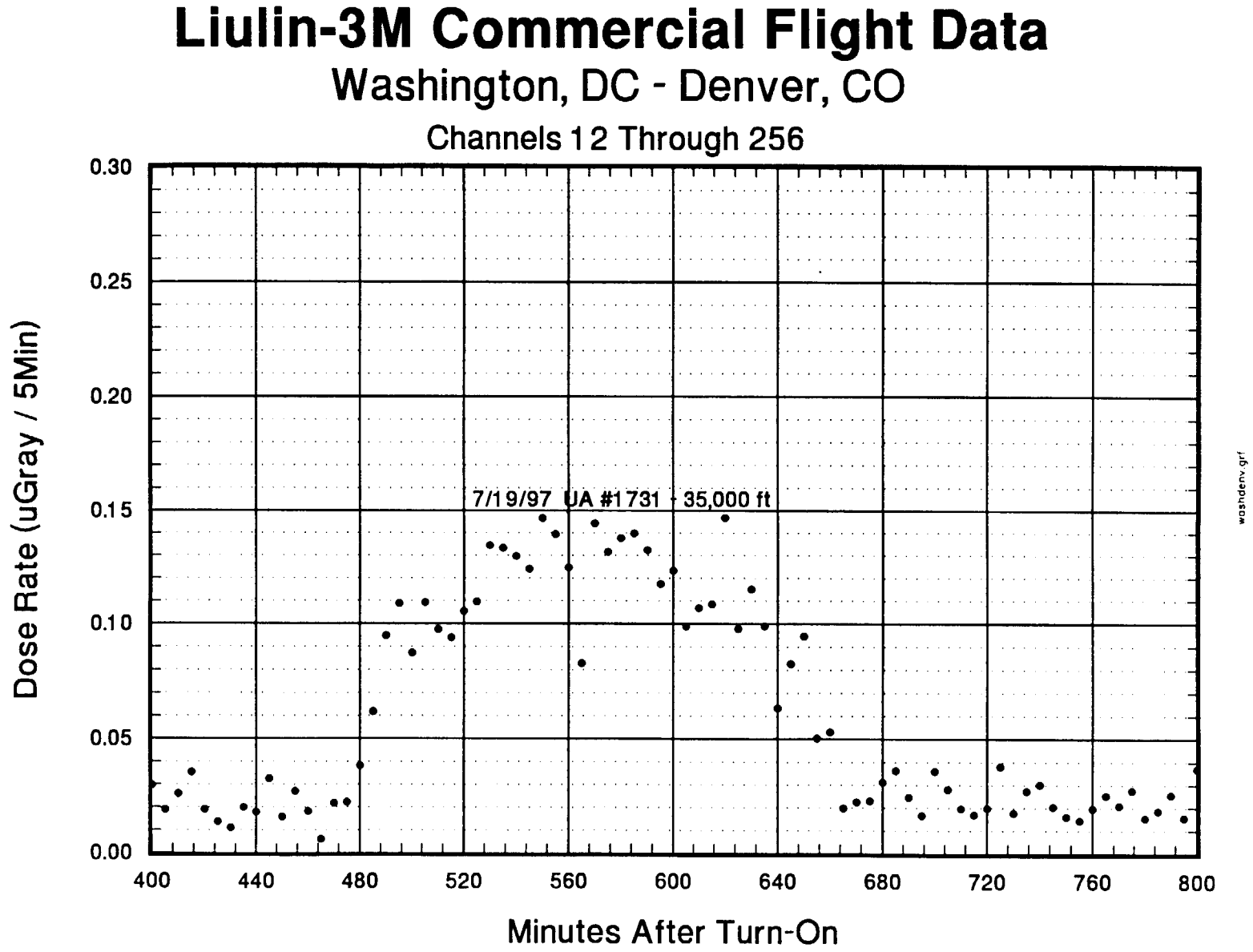
Liulin-3M Commercial Flight Data
Washington, DC - Denver, CO
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
7/19/97 UA #1731 - 35,000 ft
400
440
480
520
560
600
640
680
720
760
800
Minutes After Turn-On
washdenv.grf

FIGURE 5

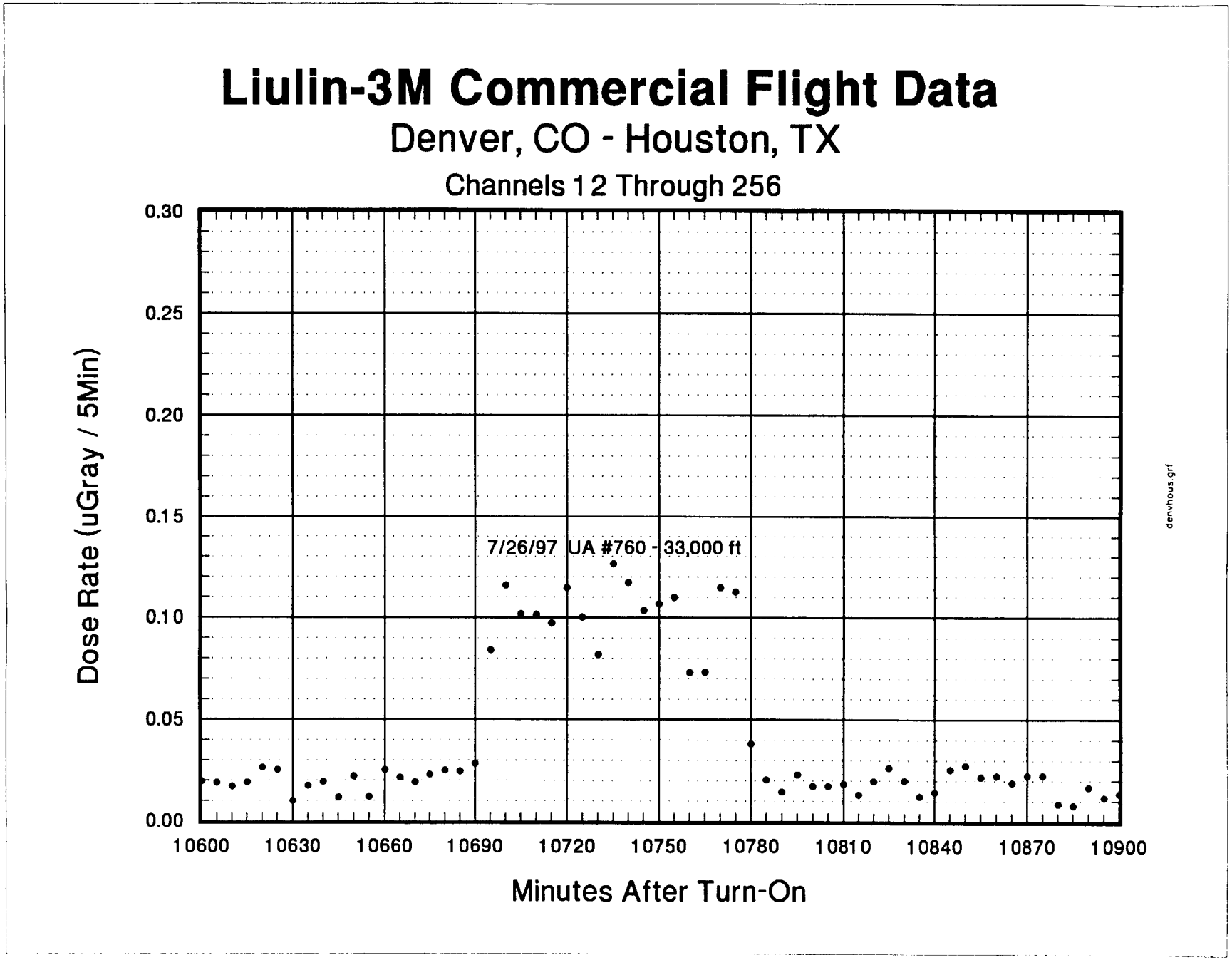
Liulin-3M Commercial Flight Data
Denver, CO - Houston, TX
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
7/26/97 UA #760 - 33,000 ft
10600
10630
10660
10690
10720
10750
10780
10810
10840
10870
10900
Minutes After Turn-On
denvhous.grf

FIGURE 6

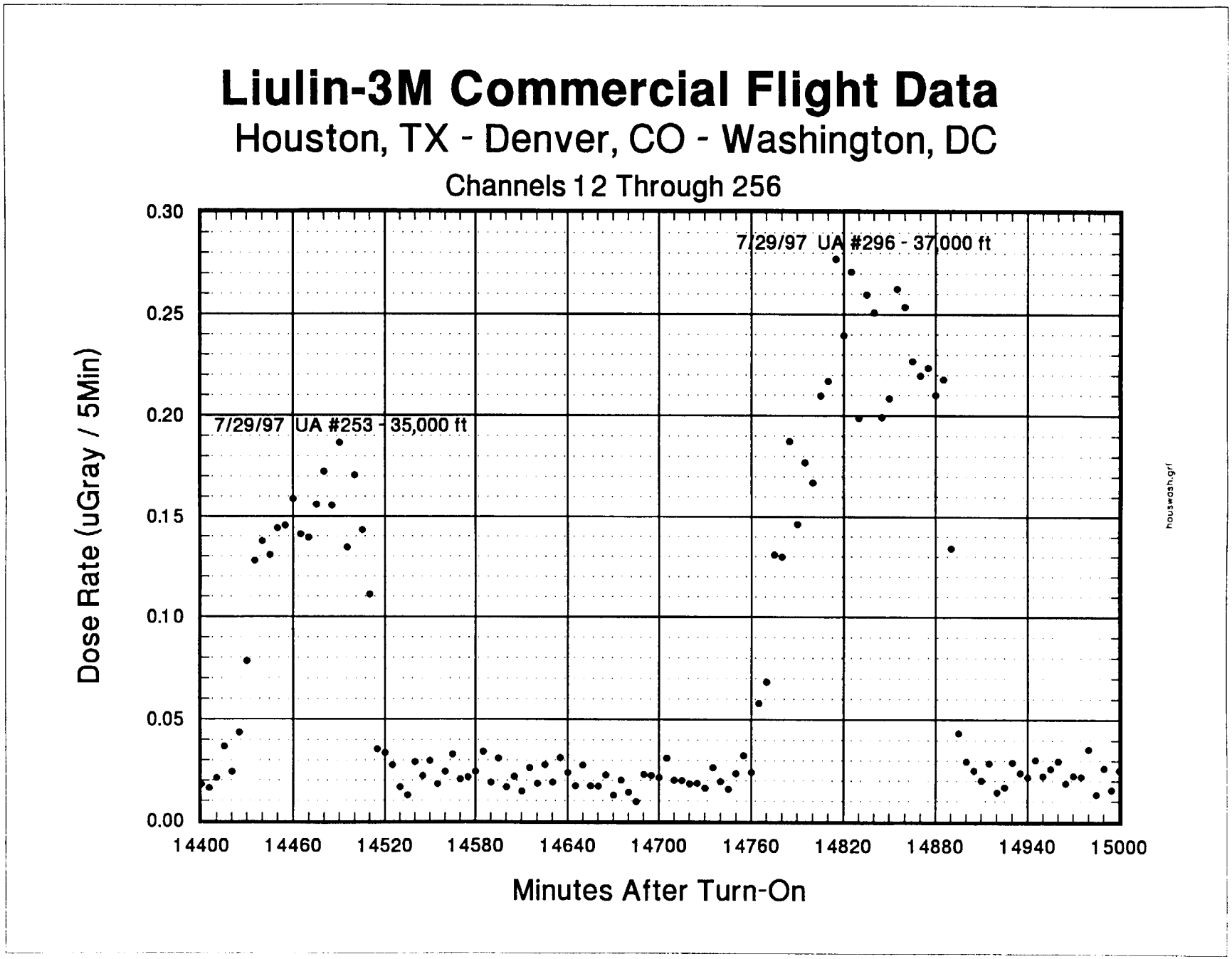
Liulin-3M Commercial Flight Data
Houston, TX - Denver, CO - Washington, DC
Channels 12 Through 256
7/29/97 UA #296 - 37,000 ft
7/29/97 UA #253 - 35,000 ft
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
14400
14460
14520
14580
14640
14700
14760
14820
14880
14940
15000
Minutes After Turn-On
houswash.grf

FIGURE 7

Liulin-3M Commercial Flight Data

Washington, DC - Denver, CO - Houston, TX - Denver, CO - Washington, DC

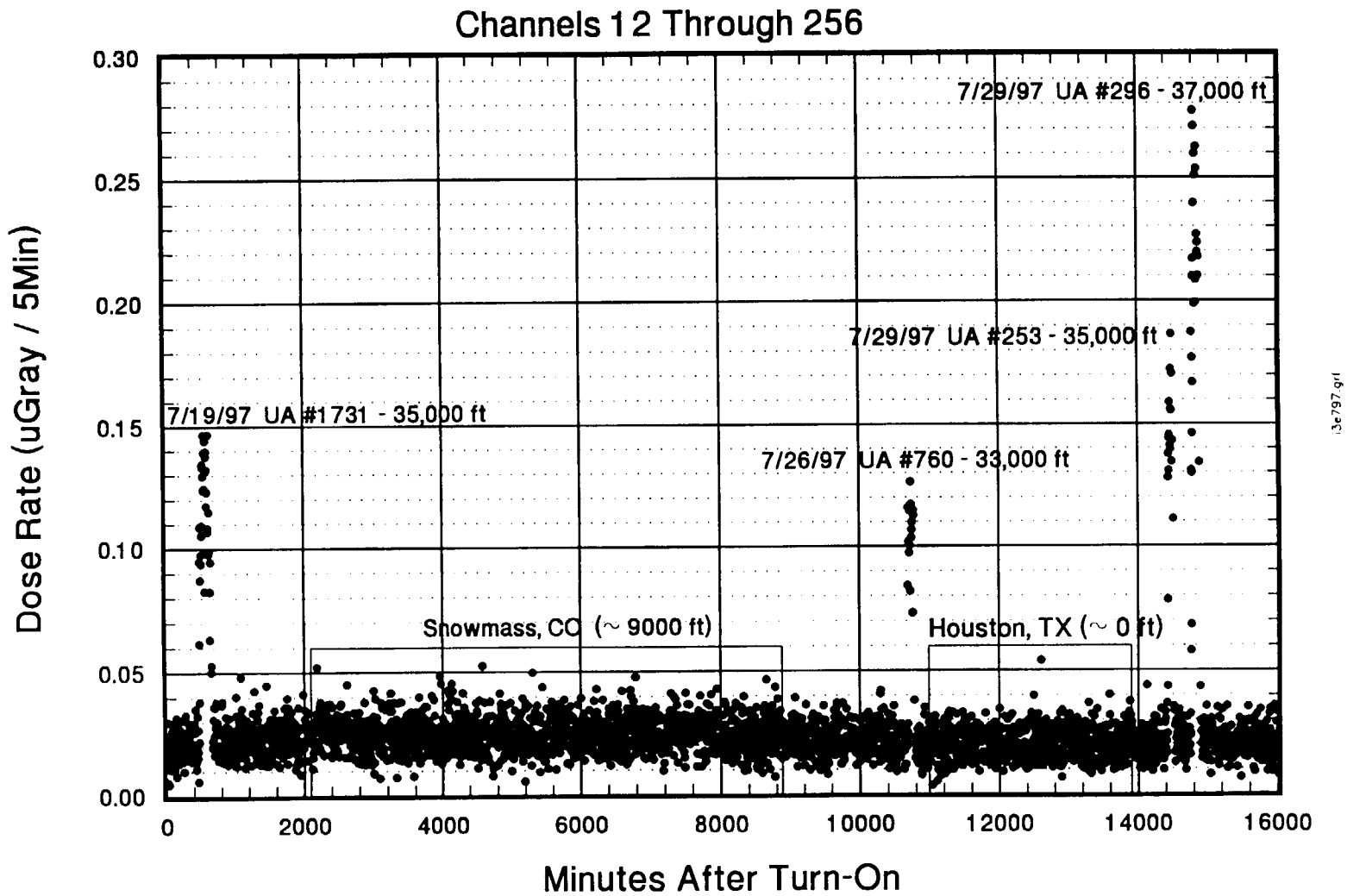

FIGURE 8

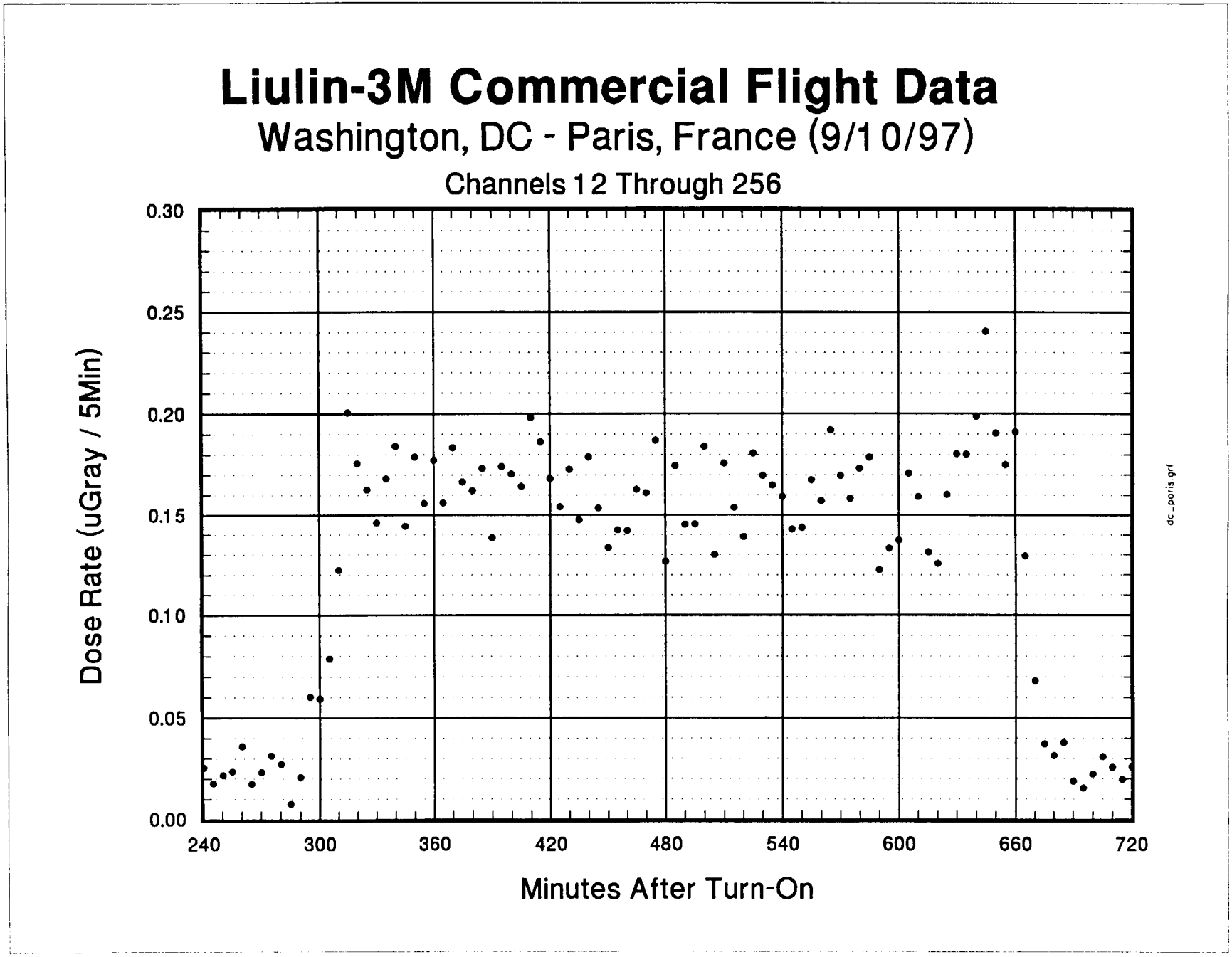
Liulin-3M Commercial Flight Data
Washington, DC - Paris, France (9/10/97)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
240
300
360
420
480
540
600
660
720
Minutes After Turn-On
dc_paris.grf

FIGURE 9

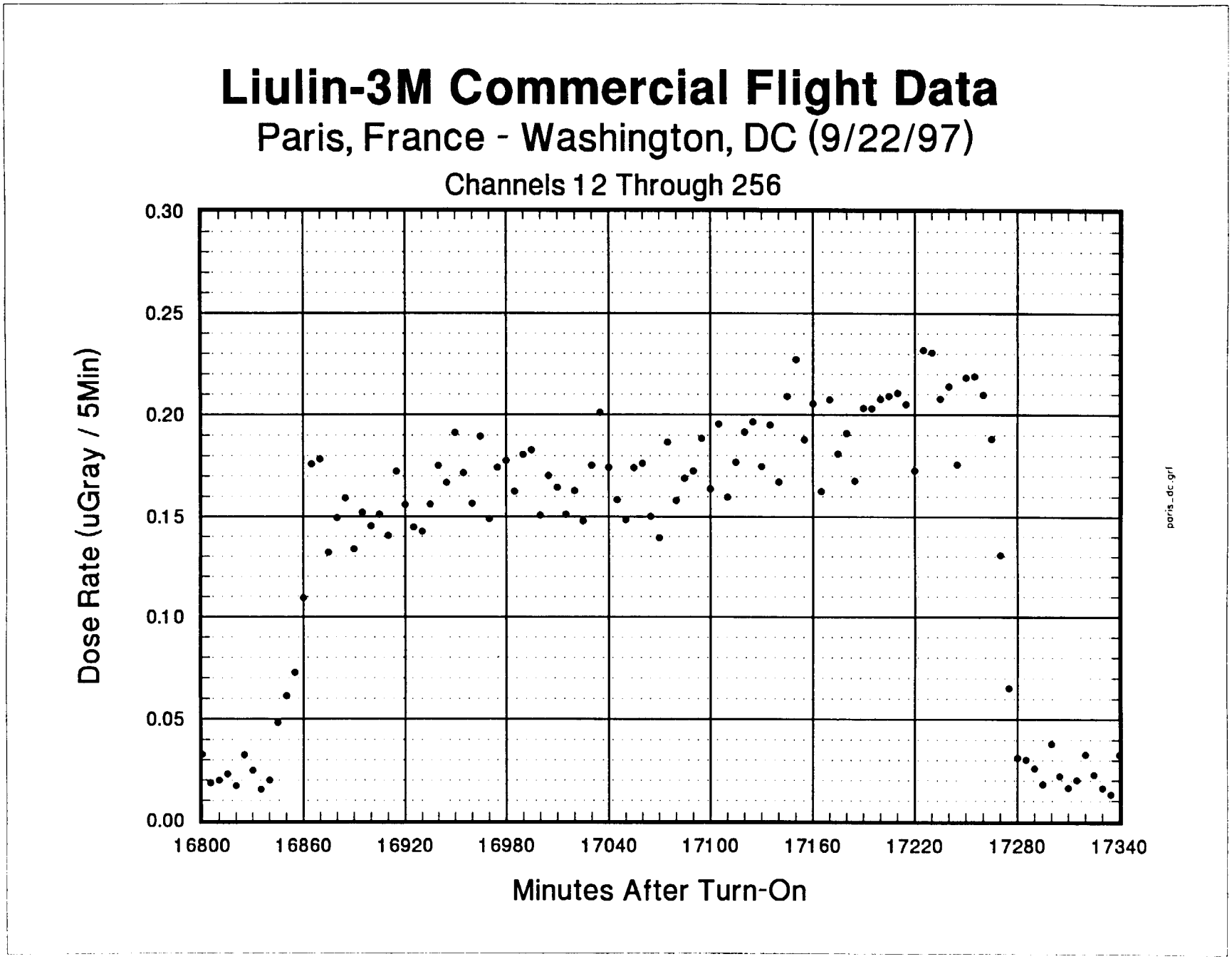
Liulin-3M Commercial Flight Data
Paris, France - Washington, DC (9/22/97)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
16800
16860
16920
16980
17040
17100
17160
17220
17280
17340
Minutes After Turn-On
paris_dc.grl

FIGURE 10

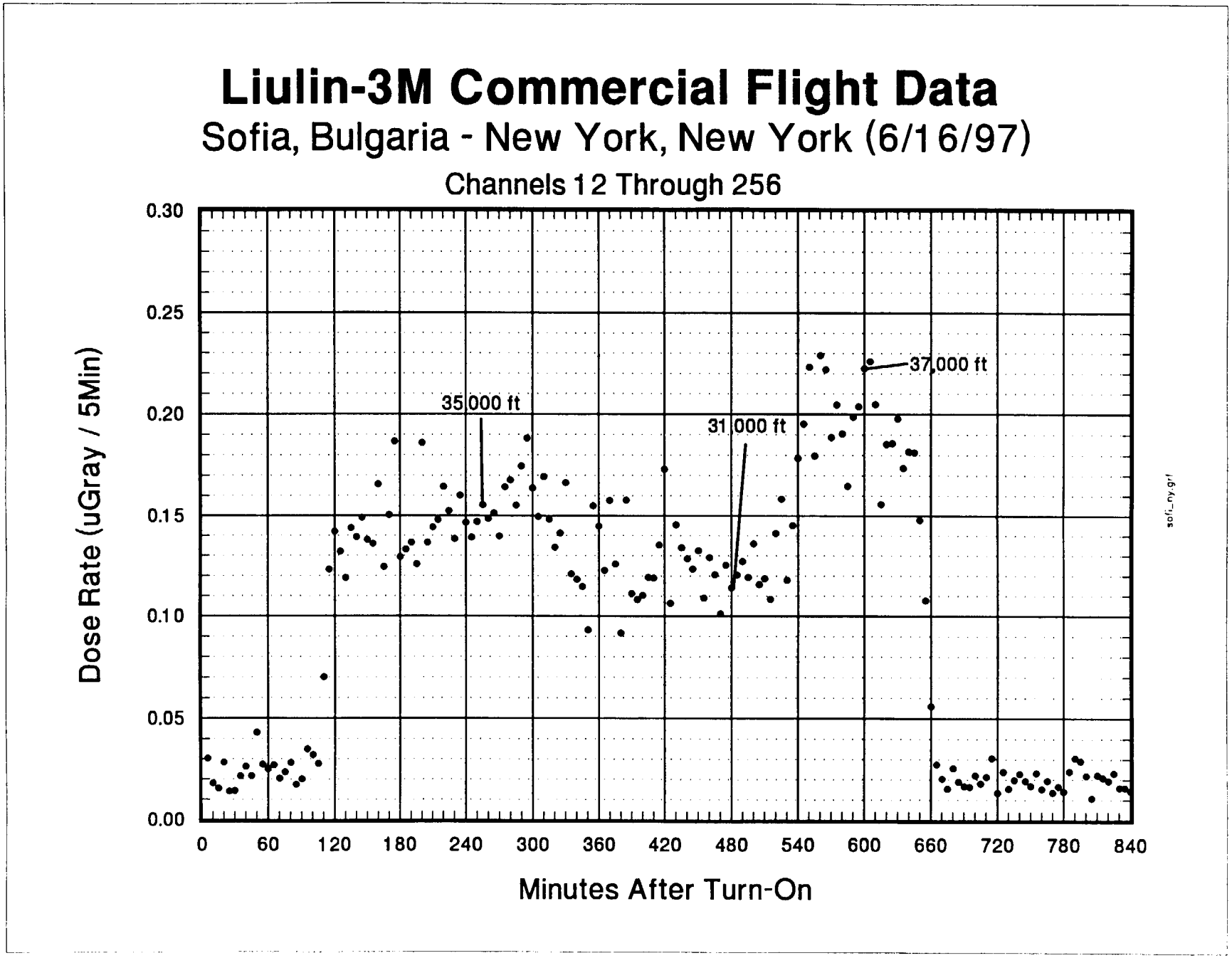
Liulin-3M Commercial Flight Data
Sofia, Bulgaria - New York, New York (6/16/97)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
35,000 ft
31,000 ft
37,000 ft
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
Minutes After Turn-On
sofi_ny.gr!

FIGURE 11

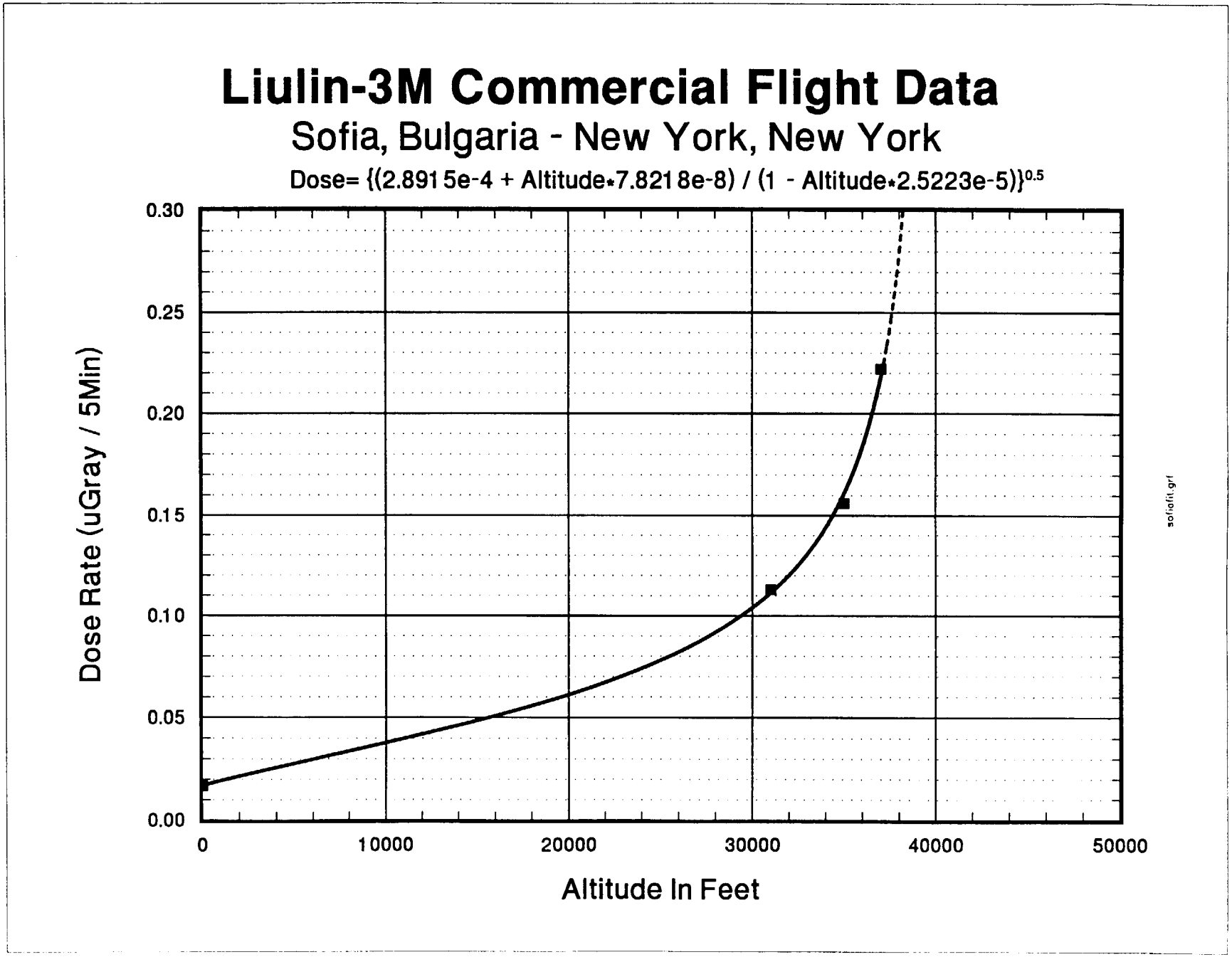
Liulin-3M Commercial Flight Data
Sofia, Bulgaria - New York, New York
Dose= {(2.891 5e-4 + Altitude*7.821 8e-8) / (1 - Altitude*2.5223e-5)}^0.5
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10000
20000
30000
40000
50000
Altitude In Feet
sofiafit.grf

FIGURE 12

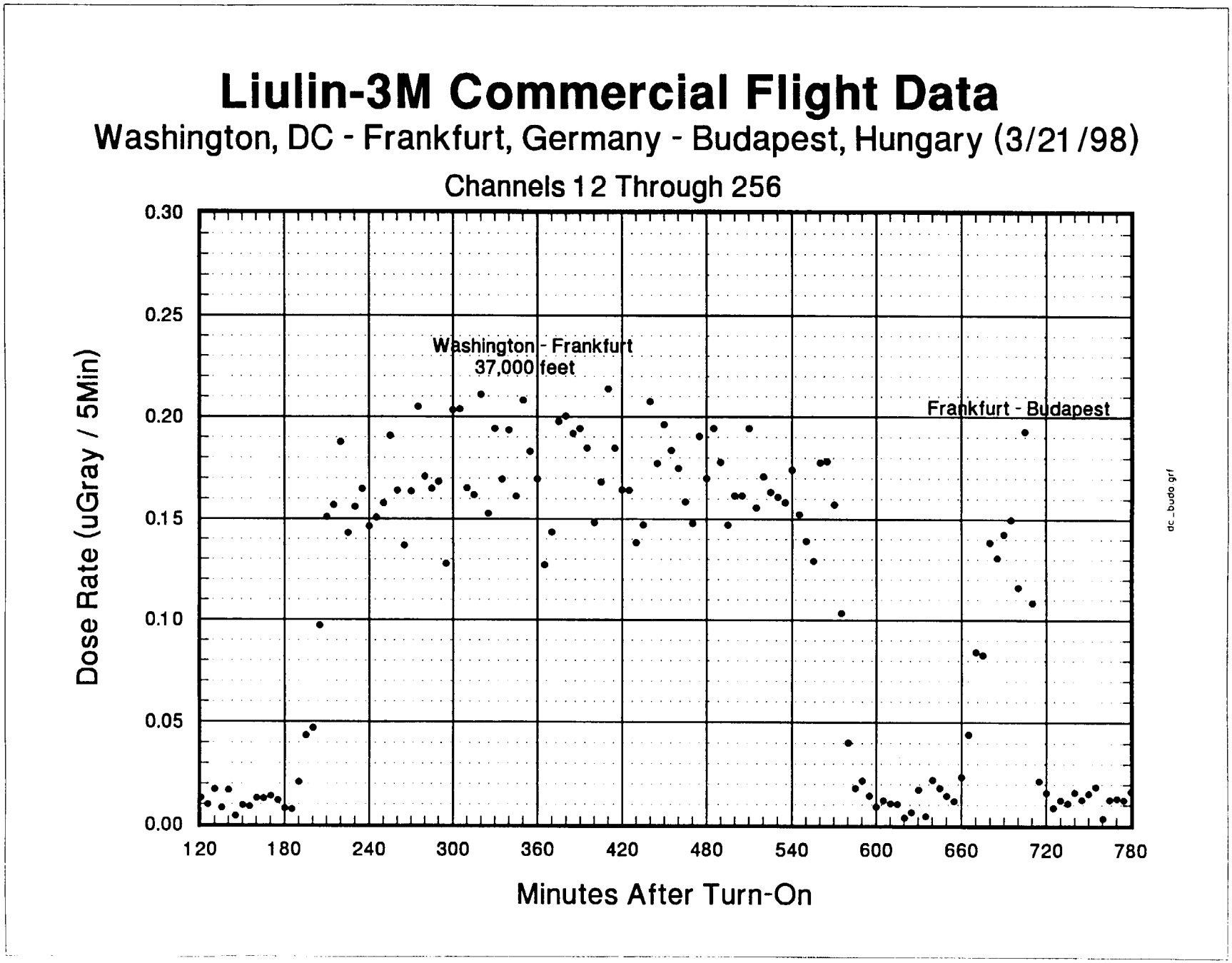
Liulin-3M Commercial Flight Data
Washington, DC - Frankfurt, Germany - Budapest, Hungary (3/21/98)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Washington - Frankfurt
37,000 feet
Frankfurt - Budapest
dc_budo.grf
120
180
240
300
360
420
480
540
600
660
720
780
Minutes After Turn-On

FIGURE 13

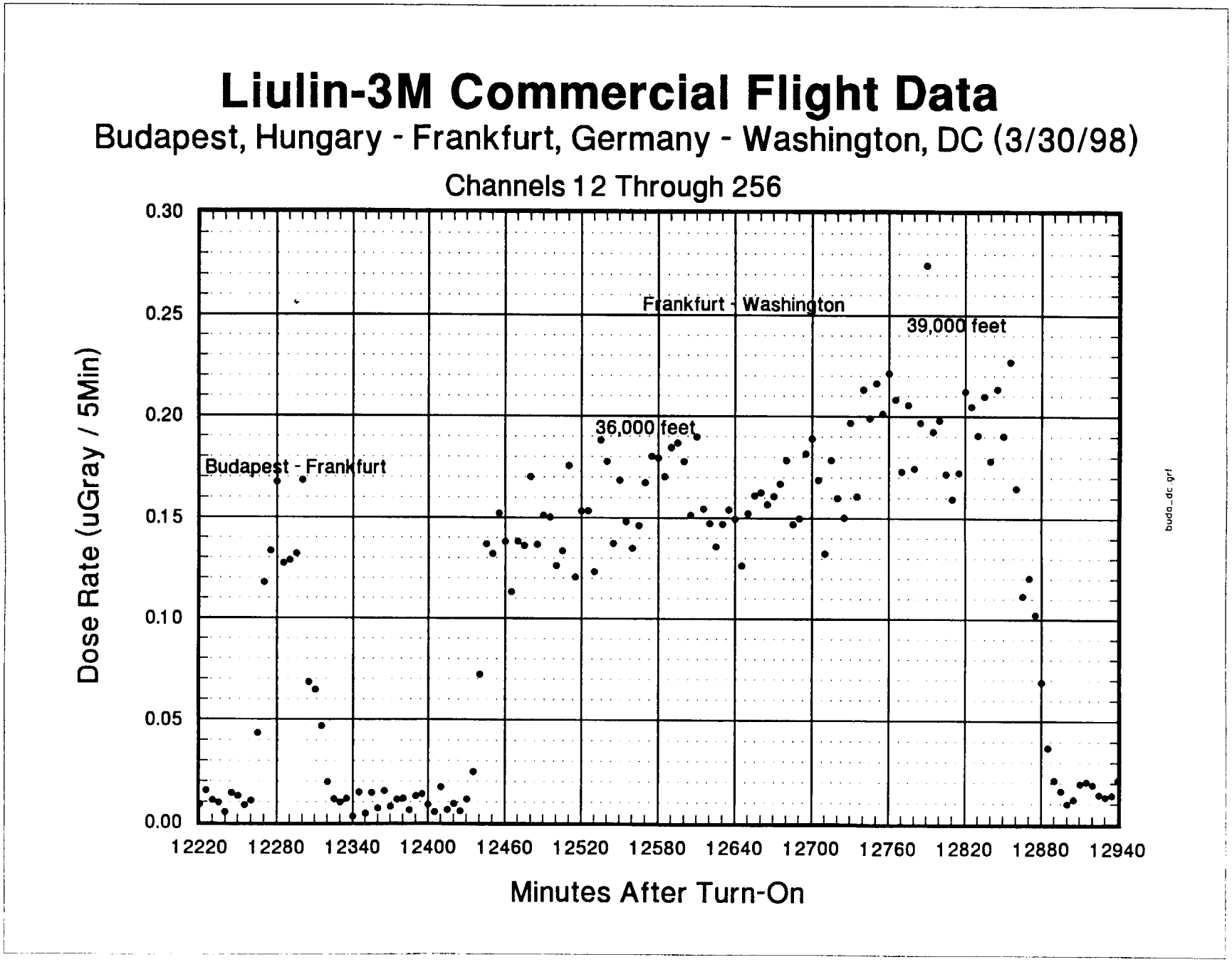
Liulin-3M Commercial Flight Data
Budapest, Hungary - Frankfurt, Germany - Washington, DC (3/30/98)
Channels 12 Through 256
Dose Rate (uGray / 5Min)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Frankfurt - Washington
39,000 feet
36,000 feet
Budapest - Frankfurt
buda_dc.grl
12220
12280
12340
12400
12460
12520
12580
12640
12700
12760
12820
12880
12940
Minutes After Turn-On

FIGURE 14